Basics of Intelligent Transportation Systems

13

13.1 Introduction

So far, the book has presented an in-depth analysis into ways to move a vehicle in different traffic scenarios, specifically the problem of trajectory planning of autonomous vehicles. The vehicle is just one entity in the entire transportation system. The transportation system comprises traffic signals, intersections, merging roads, special vehicles like public transport vehicles and emergency vehicles etc. This chapter (and chapters: Intelligent Transportation Systems With Diverse Vehicles and Reaching Destination Before Deadline With Intelligent Transportation Systems) is devoted towards a broader study of intelligent transportation systems. Although the first part of the book focussed upon everything that the vehicle could have done, with or without communication, for efficient travel through a lower level of planning; this part of the book focusses upon the advantages of an efficient higher-level planning.

The transportation system does the tedious task of transporting a large number of vehicles from their source to their destination. Traffic is highly unbalanced in the sense that the traffic for a specific direction for some time of the day and for some routes may be under heavy demand, whereas the demand for some other roads may be very light for most times of the day. This leads to slow traffic and congestion, questioning the researchers to formulate mechanisms to avoid congestion and maximize the flow of traffic. To devise mechanisms to facilitate fast and efficient flow of vehicles, it is necessary to understand the science of traffic, which also guides the driving primitives of autonomous vehicles. This chapter looks at the broader perspective of understanding the entire transportation network and its operation. In the process, the chapter talks about the utility of all the components of the transportation network like intersections, traffic lights, mergers, diversions etc. and their impact on the overall traffic. Section 13.2 discusses the basics of *traffic-flow theory* useful in the understanding of traffic.

Based on the understanding of the operation of traffic, there is a natural quest to imitate traffic on computer systems to study the effects of every traffic policy, addition of traffic infrastructure and making traffic rules without experimenting on the real traffic. The *traffic simulation systems* are used for the process. Although a large number of modules need to be designed, and the development of the overall traffic simulator is a mammoth task, in this book the modules related to different behaviours of the vehicle and other transportation system constituents are noted in Section 13.3.

The last part of the chapter carries forwards the basic concepts to the level of intelligence. It is interesting to note how each of the components of the transportation system operates and the mechanisms by which they can be made intelligent. This creates the foundation of an *Intelligent Transportation System* (ITS), wherein all the entities like vehicles, transportation management centres, traffic lights, intersection managers,

On-Road Intelligent Vehicles. http://dx.doi.org/10.1016/B978-0-12-803729-4.00013-1

merging managers, roadside units etc. can talk to each other to aid the navigation of the vehicles. This intelligence enables the vehicles to make more informed decisions about their route, navigation profile, lane changes, overtakings and driving speeds. Similarly, this intelligence enables the transportation system to move the vehicles such that congestion is minimized whereas the efficiency of the transportation system is maximized. Intelligence would be a central theme in the discussion of the transportation systems. This is done here in Section 13.4. The notion of intelligence will be carried forwards to chapters 'Intelligent Transportation Systems With Diverse Vehicles' and 'Reaching Destination Before Deadline With Intelligent Transportation Systems'.

13.2 Traffic Systems and Traffic Flow

Traffic is extremely dynamic, hosting a large number of vehicles passing through the road infrastructure at every point in time. It is possible to find congestions, deadlocks, generally slow-moving traffic etc. Considering that traffic impacts a large number of people, there have been extensive attempts to model and study traffic, thereby attempting to make operational policies which maximize the resource utilization and lead to efficient travel. It is painful to wait prolonged periods in a traffic jam, which motivates the need to have mechanisms that prevent such situations. This section studies the basic principles of traffic flow, thereby leading to the development of intelligent transportation systems. For a more detailed discussion, please refer to Immers and Logghe (2002), Lighthill and Whitham (1955a,b), Maerivoet and Moorm (2005) and Newell (1993).

13.2.1 Traffic Flow

The study of *traffic flow* deals with assessing the behaviour of a pool of vehicles constituting the traffic in different conditions. Traffic flow has been studied by numerous people coming from diverse domains. It has been extensively studied using the theory of fluid dynamics, wherein the stream of vehicles with all intersections and diversions is modelled as a fluid flow. Physicists have also modelled traffic using Particle Flow theories, assuming every vehicle as a particle and tracing its behaviour in a stream of similar particles. The control engineers model traffic as a control problem, to control the traffic network parameters to minimize congestion using control laws.

To understand the traffic flow, let us first study the simplest scenario of operation, which is a straight road with no intersections, mergers, traffic lights etc. This is also called the *uninterrupted flow of traffic*. Consider one such vehicle which is following another vehicle in front. The two vehicles are separated by a *space gap*, which is the distance between the two vehicles, from the back bumper of the vehicle in front to the front bumper of the vehicle in back. The same notion can also be defined in terms of time. A *time gap* between the vehicles is the time that the vehicle at back will take to touch the current occupancy of the vehicle in front while operating at the current speed. The two terms can also be extended to the case of multiple lanes, in which case the time gap is different for different vehicles in different lanes. The gap with the immediately left- and right-lane vehicles is important as it helps the vehicle to make decisions regarding lane changes, in some cases leading to overtaking.

Consider any particular point on the road at a particular instant of time. One could keep time constant by taking a snapshot of the current traffic and noting the vehicles ahead and behind in space. Alternatively, one could keep space constant by standing at the current position only, while noting the vehicles passing through at different time steps. This makes the *space−time graph* of the transportation system, with every vehicle denoting a trajectory in this graph showing its occupancy in space and time, shown in Fig. 13.1. The space−time graphs are widely used to assess traffic. For most readings, let us study the traffic on a road of length K till time duration of T. All vehicles falling in this space−time window are recorded for computations. Fig. 13.1 shows only two vehicles in a small observation window, whereas in most dense traffic, there will be numerous such vehicles with their trajectories displayed in the observation window.

This modelling can be used to define some macroscopic variables used for defining the macroscopic behaviour of the transportation system. The *average speed* of a vehicle is a good indicator of traffic, affecting most of the decisions. The speed can be averaged in space or in time; here averaging across space for an observed time duration is more important. The space-averaged speed ($\overline{v}$) is defined as the total distance travelled by all vehicles in the observation window, over the total time of travel of all the vehicles. This is given by Eq. [13.1].

$$\overline{v} = \frac{\sum_i x_i}{\sum_i T_i} = \frac{\sum_i v_i dt}{\sum_i dt} = \frac{\sum_i v_i}{N} \qquad [13.1]$$

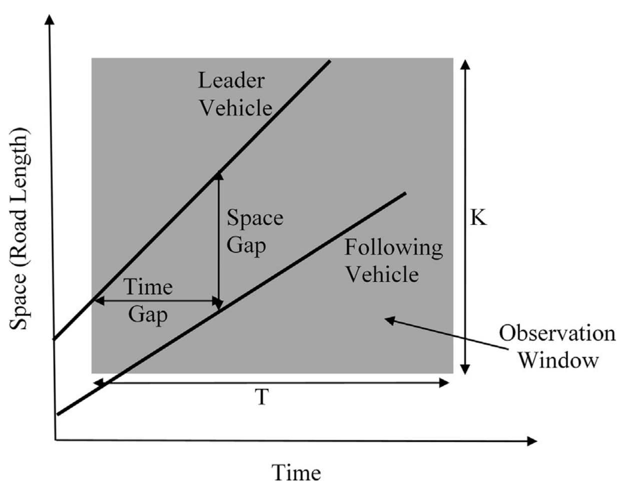

Figure 13.1 Space−time graph for traffic.

Here, x_i is the distance travelled by the vehicle i, T_i is the time of travel of vehicle i. v_i is the average speed of vehicle i. The second term of the equation is for an observation window of time dt.

Density (k) is the number of vehicles per unit length. It is measured by the number of vehicles (N) in a small observation window, over the length of the small observation window (K). If the road has multiple lanes and N_i is the number of vehicles in lane i, the density (k) is given by Eq. [13.2]

$$k = \frac{N}{K} = \frac{\sum_i N_i}{K} \qquad [13.2]$$

The above density is based on space, wherein we keep a constant snapshot of time and measure the density for some region of space (road). The density can also be defined in terms of time, wherein the density is the total time spent by all vehicles in a small region, over the area of the observation region. This formulation is given in Eq. [13.3].

$$k = \frac{\sum_i T_i}{Tdx} = \frac{\sum_i \frac{dx}{v_i}}{Tdx} = \frac{1}{T}\sum_i \frac{1}{v_i} \qquad [13.3]$$

Here, T_i is the time spent by vehicle i, v_i is the average speed of vehicle i. The equation is for an observation made in a space of length dx for T units of time.

Flow is the number of vehicles passing an observation point per unit time. The flow (q) is given by Eq. [13.4].

$$q = \frac{N}{T} \qquad [13.4]$$

The flow can also be defined as the distance travelled by the vehicles in an observation window, over the area of the observation window. The relation is given by Eq. [13.5].

$$q = \frac{\sum_i x_i}{Kdt} = \frac{\sum_i v_i \cdot dt}{Kdt} = \frac{\sum_i v_i}{K} \qquad [13.5]$$

Here, x_i is the distance travelled by vehicle i. The calculation is done for a road of length K and for a time duration of dt. The density and flow may be added over the number of lanes, and time averaged over an observation duration.

The traffic-flow theory is based upon a *fundamental relation* between the three entities, mean speed, flow and density. This enables conversion from one to the other to understand the traffic flow. The relation is given by Eq. [13.6].

$$q = k\overline{v} \qquad [13.6]$$

The traffic is assumed to be homogeneous over the road network and stationary for some time. This can happen when the conditions are stationary and the traffic shows no change in trend in terms of density, flow and speed. When the vehicles leaving become fewer than the vehicles entering, there is a mismatch and queues start to form. Alternatively, the queues can clear when the flow of vehicles outside is more than the flow entering.

Floating cars are widely used to record the real traffic data in a transportation network. These are special vehicles which are deputed to move around and record the essential parameters of traffic, based on which the condition of traffic can be assessed.

13.2.2 Fundamental Diagrams

Traffic operates in multiple phases and states, the properties for which change with time depending upon the demand dynamics. To understand traffic flow, let us start with an empty road with no vehicles such that the density is zero. Let us slowly add vehicles such that the density increases. Even though the number of vehicles and thus the density increases with time, because the road in such a state is so sparsely occupied that the vehicles are hardly affected by each other. This stage is called the *free-flow traffic*, and is characterized by small density and high flow, whereas the mean speed is close to the preferred speed of the drivers. On increasing the density, the flow increases as the number of vehicles increases with time, whereas there is a very small drop in the mean speeds. On further increasing the density, the network reaches a threshold flow, which is the maximum flow that the network can sustain and is called the *capacity flow*. The mean speed reduces in this region.

Suppose the traffic density is increased even further by packing in more vehicles. This results in smaller distances maintained between the vehicles. As a result, the drivers have to slow down. Thus, further increase in traffic leads to a severe drop in speeds and a situation of *congestion*. Severely increasing the number of vehicles can cause jammed traffic, wherein the distances between the vehicles is very small and the vehicles are nearly always in a state of rest.

Consider that the density at a region of road is suddenly increased, which will make the vehicles of the region drop their speeds. Common examples are traffic lights, mergers and blockages. This produces commonly seen *shock waves*. As a result, the vehicles behind will also drop their speeds. In the worst cases, the speed will become zero, in which case the vehicles will staring queueing one after the other. This is a shock wave which travels from the front to back. If a pool of vehicles continues to move a small distance, the wave will propagate backwards and the vehicles will start moving in a wave-like manner, creating a stop-and-go wave. On the contrary, consider that the traffic suddenly clears and now it is possible for a pool of vehicles to have free-flow travel as the vehicles ahead have suddenly cleared or a blockage is cleared. In this case the vehicles start moving and clearing the way for other vehicles which further start moving. Going forwards in space, one sees the speed continuously increase. This cases a kinematic wave to travel forwards with vehicles possessing high speeds. In traffic systems, such upstream and downstream waves are continuously produced and propagated. The waves from different sources may merge and cancel each other's effect, or add up and traverse. The waves maintain their own speeds and effects.

Based on the previous discussion, it is intriguing to study the behaviour between mean speed, flow and density under different conditions. A plot between these quantities is called a *fundamental diagram* and represents the basic fundamental principles behind the operation of traffic. The first fundamental diagram is between traffic density and mean speed. To plot the graph, start with a very small density, in which case the speed will be very high. As one starts to pack more vehicles, the intervehicle separation starts to decrease, resulting in the vehicles having to reduce their speed. In this duration the vehicle makes a transition from free flow to a capacity flow and finally to a congested flow wherein the speeds are nearly zero. A generic figure showing the relation is given in Fig. 13.2A.

The next diagram is between traffic flow and traffic density. Initially, when the density is very small, the vehicles move with their free-flow speeds. However, because the number of vehicles is small, the flow is small. An increase in the traffic density increases the flow, till the network starts exhibiting the maximum capacity flow. Any further increase in traffic density causes the traffic flow to reduce, till it reaches the congested level, wherein the vehicles stop moving and correspondingly the flow is zero. The diagram is shown in Fig. 13.2B.

The last diagram is between the traffic flow and mean speed. This diagram is interesting. A very low traffic flow is an indicative of a very congested traffic scenario

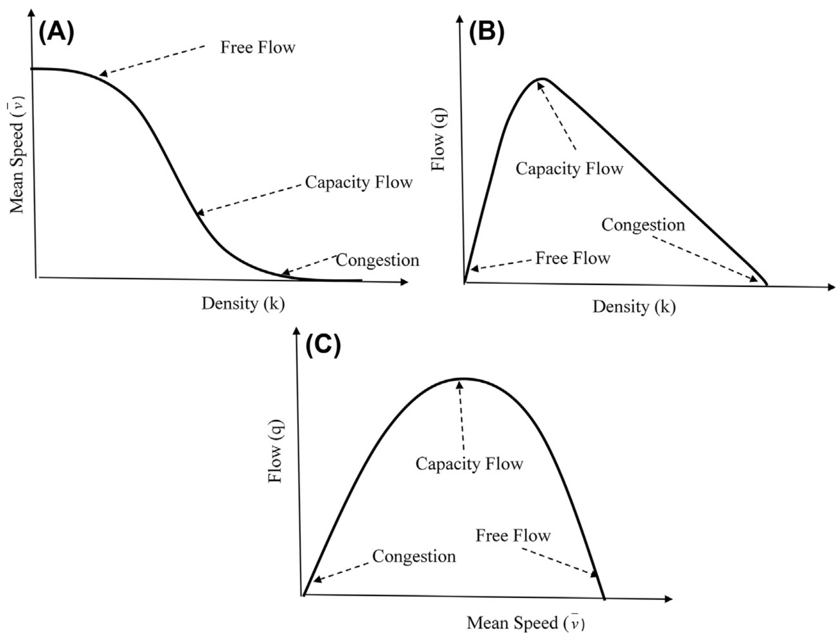

Figure 13.2 Fundamental diagrams: (A) mean speed versus density, (B) flow versus density, (C) flow versus mean speed.

wherein the speeds of the vehicles are nearly zero and the density is alarmingly high. It is also possible to get very small traffic flow when the vehicles are operating at high speeds, but the density is far too low making the flow small. The former is the case of a congested phase, whereas the latter is a case of free-flow phase. As the vehicle goes from the free-flow region to a capacity-flow region, the speed reduces due to the insertion of more vehicles. However, the flow constantly increases till it reaches the capacity flow. Any further increase in density will cause vehicles to show signs of congestion and they will start slowing down, also reducing the flow. This happens till a jam occurs and all vehicles nearly stop, creating zero traffic flow. An indicative diagram is shown in Fig. 13.2C.

13.2.3 Interrupted Traffic Flow

The traffic system discussed so far was based on a single road, with all vehicles travelling on it. This is an uninterrupted flow of traffic. In the real world, the normal traffic flow is *interrupted* by conditions such as traffic lights, mergers, diversions, intersections etc. The case of mergers and diversions is particularly interesting, which results in either a new source of vehicles to feed in or an alternative way for vehicles to feed out. Consider the case wherein two roads merge into one, meaning the traffic from both roads is expected to merge and make a single flow. Consider a main road on which a ramp road merges and adds traffic. Let k be the density and q be the flow of the main road. Let the ramp road feed in vehicles at the rate of z per unit length and per unit time. We know that the number of vehicles in the main road after merger will be the vehicles given by the main road before merger and the ones given by the ramp road, also accounting for any change in flows in the process. Note that here z is expressed in per unit time and space both, hence the units. Formally, this law is given by Eq. [13.7] and is the *fundamental law of traffic with external sources*.

$$\frac{\partial k}{\partial t} + \frac{\partial q}{\partial x} = z \qquad [13.7]$$

The conditions of traffic lights are interesting. The stoppage due to traffic lights causes the traffic of a particular road to stop, sending a shock wave downstream. As a result, the vehicles start to queue. The green light results in clearing up of the traffic, sending another kinematic wave upstream wherein the vehicles start to clear up.

13.2.4 Congestion

Congestion (Güner et al., 2012; Skabardonis et al., 2003) is commonly seen in traffic, wherein the traffic barely moves. Congestion can be very troublesome for people. Congestion arises when there are too many vehicles entering the road network, whereas the same outflow cannot be accomplished. This results in queueing in the road network, thereafter leading to more congestion. The congestions may be classified as recurrent and nonrecurrent. *Recurrent congestions* are the ones which are repetitive and occur in patterns. Say a place has a large number of people going to the office in the morning in the same direction, which dramatically increases the number of vehicles on the road causing congestion. This pattern is observed every day. The recurrent congestions happen due to prior known causes and can be predicted. People are normally aware of the recurrent congestions and account for the same before making travel decisions.

NonRecurrent Congestion arises due to reasons unaccounted for a priori and because such congestion shows no trends, it cannot be easily computed in advance. The nonrecurrent trends are caused due to factors such as accidents on a road, blockage of a road due to various reasons, public demonstrations, public events, adverse weather conditions etc. Such congestions suddenly arise and cause a great deal of discomfort to people. As the entire road network is connected, congestion at one place can severely affect the traffic flow at other places as well.

13.3 Traffic Simulation

Traffic simulation studies are widely used to imitate traffic on natural and synthetic scenarios and to experiment with different operational policies to understand the effect of those policies (Jaume, 2010). The traffic may be studied from a microscopic or macroscopic perspective. The *microscopic* study of traffic models each vehicle as an independent entity, which interacts with the other vehicles in the vicinity. The motion is affected by conditions such as intersections, traffic lights, mergers and diversions. On a straight road, the intention is largely to model the vehicle flow based on the separation from the vehicle in front. This is the simplest car-following behaviour, wherein the immediate speed of the vehicle depends upon the speeds of the two vehicles and their distances. The other behaviours can be similarly modelled. Microscopic traffic simulation gives the ability to study the individual vehicle behaviours based on traffic studies and to imitate the same in a computational framework.

The *macroscopic* traffic simulation models the vehicles as a dense flow, dealing with the average speed and density of vehicles at every intersection. It concerns the interaction, building up and clearing of the vehicle density due to different scenarios. The flow, overall, is modelled, rather than a collection of individual vehicles. The *mesoscopic* traffic simulation models combine the two methodologies of microscopic and macroscopic simulation and enable controlling the individual vehicle behaviours while operating as a flow of vehicles.

Traffic simulation requires a number of modules to be developed, which knit together enable simulation of the entire road-network graph for a long duration of time. One of the most important modules is the car-following module, showing the dynamics of a vehicle when it follows another vehicle. The basic module is supplemented with the modules of lane change, merging, traffic lights, intersection management, pedestrian handling, routing etc. The important modules and concepts are illustrated in the following subsections. The intelligence in Intelligent Transportation Systems is added on top of these modules. The intelligent aspects of some of these constituents are discussed in Section 13.4.

13.3.1 Basic Concepts

The traffic simulation systems take as input the road-network graph of the place. The data for the same can be obtained from multiple places like Openstreetmap (2015) and are also publically available for a large number of cities. The roads may have information about the lanes, speed limits, whether it is a one-way, whether overtaking is permitted etc. The road-network data are supplemented with the specification of the controlled and uncontrolled intersections, pedestrian crossings, car parks etc. The data may be noisy, and therefore the simulation is expected to filter out the data to remove errors like roads which are not connected to any other road, estimation of the presence of traffic lights, identification of intersections from raw files etc.

To simulate the network, we need to generate some traffic. The data about the traffic is specified by an *Origin−Destination* (OD) *matrix*. The matrix contains the number of vehicles going from every origin to every destination on the map for every unit time. The matrix is loaded onto the simulation, which generates such a source stream of vehicles for the specified time. The destination consumes the vehicles as the vehicles disappear from the network on reaching it. A road map of Reading, United Kingdom, and a simulated OD matrix is shown in Fig. 13.3.

The first problem associated with simulation is to convert the OD matrix into flows for different regions of the network at different points in time. This problem is called

(A)

(B)

Origin	Destination						
	d_1	d_2	d_3	d_4	………	d_n	Total
o_1	0	87	56	76	………	15	445
o_2	34	0	15	32	………	32	334
o_3	54	29	0	76	………	33	653
o_4	75	84	39	0	………	43	143
…….	….	….	….	….	………	….	
o_n	45	34	66	27	………	0	732
Total	765	567	676	456	………	556	10065

Figure 13.3 Inputs for traffic simulations: (A) road network graph and (B) origin destination matrix.

the *traffic assignment* problem. To make their travel every vehicle must select the route to travel through, which is called the problem of *routing*. The person may prefer to take not only the shortest routes, but also routes which do not have much traffic, hence the congestion is low, and the operating speeds are high. So the routing decisions are based on the network model and the demand model of the system. The route information can be used for loading the network with the vehicles as per the given OD matrix and choice of route.

Consider a case wherein there is a short road connecting some origin and destination, which is a route normally under heavy demand and therefore congested. In such a case, the speeds of the vehicles on the route will be low and the time of journey will be long. Now suppose a vehicle decides to take a longer route, and reaches the destination earlier due to the less-congested state of the longer route. This encourages more vehicles to take the longer route in pursuit of reaching the destination early. This will finally end in an equilibrium, wherein the longer route will be as good an option to take as the shorter route considering the combined effect of journey time, convenience, fuel cost etc. In general, for a transportation network, for every origin and destination in the OD matrix, if the utility of two vehicles departing at the same time is equal and highest across all options offered by the network, the traffic flow is said to be in a state of *Dynamic User Equilibrium* (DUE). The traffic assignment must hence take care that such an equilibrium is maintained. Any change in the equilibrium must be dynamically managed by readjusting the traffic at the alternative routes.

13.3.2 Intelligent Driver Model

Based on the fundamentals of traffic flow, numerous models have been developed over the years. These models enable the simulation of traffic. The most dominant and hard to model behaviour is the vehicle-following model. The *Intelligent Driver Model* (Treiber et al., 2000) is one such model widely used for traffic simulation and analysis. The model computes the motion of a vehicle in the state when it is following another vehicle in front. The model can be naively extended to the situation of travelling on a free road, wherein there is no vehicle in front. The model accounts for the general equation for vehicle driving which states that once the driver perceives some stimulus from the environment, there is a lag of reaction time from the driver during which time no actions are made. After the reaction time, the driver responds to the stimulus by making an appropriate action, based on the driver's sensitivity. This is given by Eq. [13.8].

$$\text{Response}(t + t_r) = \text{Sensitivity} \times \text{Stimulus}(t) \qquad [13.8]$$

Here t is time and t_r is the reaction time.

The Intelligent Driver Model uses the concept of a safe distance, which is the distance ($s*$) that the vehicles prefer to maintain. The safe distance is given by Eq. [13.9].

$$s* = s_0 + s_1\sqrt{\frac{v}{v_0}} + Tv + \frac{v\Delta v}{2\sqrt{ab}} \qquad [13.9]$$

Here, s_0, s_1, v_0, T, a and b are constants. Δv is the relative speed of the vehicle with respect to the vehicle in front and is given by the speed of the following vehicle minus the speed of the vehicle in front. It is also called the approaching rate. The first term s_0 is the minimum safe distance that the vehicle always maintains with the vehicle in front, even if both the vehicles are stationary in a jam situation. The second term $s_1\sqrt{\frac{v}{v_0}}$ is not very intuitive and suggests that higher speeds require more safe distance. The third term Tv is the distance that the vehicle will travel with the current speed till a moderate time T, which must be maintained. This accounts for the reaction time. The last term accounts for a vehicle moving with a general acceleration given by the maximum acceleration (a) and braking (b) terms, while the vehicle is travelling with a general speed given by the approaching speed Δv and the current speed v.

The vehicle may not be maintaining the preferred distances and therefore will have a tendency to brake or accelerate in response to the situation. The vehicles have a tendency to accelerate if the road is free with a value given by Eq. [13.10].

$$\mathrm{acc} = a\left(1 - \frac{v}{v_0}\right)^{\delta} \qquad [13.10]$$

Here, δ is a constant. The equation states that, everything kept aside, a higher velocity means a smaller magnitude of acceleration.

The vehicles also have a tendency to brake if the current distance is much smaller than the desired distance given by Eq. [13.11]

$$\mathrm{brake} = -a\left(\frac{s^*}{s}\right)^2 \qquad [13.11]$$

The equation suggests that the smaller the distance in contrast to the preferred distance, the larger is the retardation or braking. The resultant acceleration model displayed by the vehicle by the application of brake and throttle is thus given by Eq. [13.12].

$$\dot{v} = \mathrm{acc} + \mathrm{brake} = a\left[\left(1 - \frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*}{s}\right)^2\right] \qquad [13.12]$$

13.3.3 Other Modules

The other modules are well illustrated either as already discussed in the book or in the following sections/chapters. Therefore, the modules are very briefly summarized here. *Lane change* is one of the dominant modules which plays a major role in everyday traffic. Lane-change behaviour involves decisions whether to change lanes, which lane to change to and thereafter the trajectory of lane change. The decisions are based on time to collision, time and space gaps, density of vehicles, length of queues etc. *Overtaking* is another module dealing with whether to overtake and thereafter the overtaking trajectory. The *merging* module handles the vehicle behaviour when two roads merge into one. The mergers may be controlled or uncontrolled. The decisions involved are whether the main vehicle goes next or the ramp vehicle, and thereafter the trajectory for each of these. Similarly, *diversions* deal with the situations when the road diverges. *Intersections* may similarly be controlled or uncontrolled. In case of controlled intersections, the operation of traffic lights is very important. The *traffic light* policies are also simulated by the simulator.

The problem of *routing* deals with deciding the fastest, shortest and most economical (in terms of tolls or fuel) route for the vehicle considering the predicted traffic data. The modelling of *pedestrians* is another important feature as at many places pedestrian traffic severely affects the main traffic. Ways of dealing with *unexpected situations* like road blockages, special incidents, emergency vehicles and public buses on public bus-only lanes are other important aspects of traffic simulation.

13.3.4 Empirical Studies

So far, many constants and parameters have been introduced. Some of these parameters are controlled, the values for which depend upon the operational traffic policy, whereas some others are uncontrolled. The aim is to make a traffic simulation system using policies such that the performance is maximized for the controlled variables. Here, the performance may be given by many factors including the efficiency of the system, safety, economy etc. The uncontrolled variables cannot be controlled by the transportation centres, and the network is operated such that the expected performance is maximized against all values of these variables.

All the constants depend upon the vehicle. One may assume that the transportation system has all vehicles of the same nature and therefore assume the constants to be the same for all vehicles. This facilitates easier study of the network, not having to compute a large number of parameters. To fix the parameters, traffic data are collected over a number of roads and a number of scenarios. The data will require filtering to remove noise. The traffic data are used to compute the values of the parameters. This process is called calibration. *Calibration* may be different for each module in complex models. The techniques give the best fit of the parameters which make the assumed model behave closely with the real-world model recoded by the data.

13.3.5 Common Traffic Simulators

Numerous research groups worldwide have developed a number of traffic simulation tools, which can be used straightaway for carrying traffic simulation. These tools are extensively used to assess the utility of changing the transportation operation policies and rules, new infrastructure in terms of roads and public vehicles, and further enabling study of the effect of addition of intelligent constituents in the otherwise nonintelligent transportation system. One of the popular open-source traffic simulators is Simulation of Urban Mobility (SUMO) (Krajzewicz et al., 2012) from Germany, which allows all features mentioned while using microscopic simulation. Other popular simulators include Dynamic Route Assignment Combining User Learning and microsimulAtion (DRACULA) (Liu, 2005), Microscopic Traffic

Simulator (MITSIM) (Ben-Akiva et al., 2010), Traffic in Cities Simulation Model (VISSIM), PARAllel MICroscopic Simulation of Road Traffic (PARAMICS), Advanced Interactive Microscopic Simulator for Urban and non-urban Networks (AIMSUN), DYNAMic EQuilibrium (DYNAMEQ) etc.

13.4 Intelligent Constituents of the Transportation System

This section specifically focusses on the intelligence part of the transportation system. Although the theme of intelligence of transportation systems will continue to chapters 'Intelligent Transportation Systems With Diverse Vehicles' and 'Reaching Destination Before Deadline With Intelligent Transportation Systems', some of the notable and basic concepts are highlighted here for motivation. Section 13.3 mentions numerous modules necessary for traffic simulation, which are ultimately obtained from the operation of real-life traffic. This section and the next two chapters focus on specific constituents and investigate the application of intelligent concepts that make the overall transportation system intelligent.

13.4.1 Intelligent Traffic Lights

Traffic lights play a major role in management of the traffic. Without traffic lights, dense traffic would come from all sides of the road and would block the intersection without letting any vehicle pass through. The traffic lights allow and disallow traffic, based on time, to pass through the intersection. The duration and order of change of the traffic light is very important. The problem with the current orthodox traffic light systems is that the traffic light period and order are predefined. The order may be made to change at different times of the day. However, intelligent traffic lights can look at the traffic density at the different roads around and itself decide the order and duration of the traffic light. These traffic lights are facilitated by live inputs like the queue length at different roads. This can be accomplished by a variety of ways including the use of loop detectors at different roads, video-processing techniques etc.

There are two methodologies to work with intelligent traffic lights. One could consider a microscopic approach wherein every traffic light is dealt with independently and each traffic light decides its own operation policy based on the current input of traffic. Alternatively, macroscopic systems consider a set of traffic lights as one system and simultaneously generate an operational policy for all of them, such that the performance of the overall system is maximized. This methodology enables one traffic light to avoid sending too many vehicles too early to another traffic light, which will not be easily able to consume all vehicles at such a large pace. These traffic-light—traffic-light interactions can be modelled by the approach.

The problem of deciding the traffic light operation time and order is a decision-making problem. In this problem, the different parameters affecting the decision like queue length, priority of vehicles, traffic density, number of lanes, predicted traffic etc. are given as inputs to an intelligent system, which needs to assess these inputs and accordingly decide the output, which is the green-light time and the order of operation. One of the simple ways to solve the problem is by using Fuzzy Inference Systems (Collotta et al., 2015; Nair and Cai, 2007; Trabia et al., 1999), which use rules that can be handcrafted and tuned to get a good performance over different mixes of traffic densities. The tuning of rules is done to maximize the performance measure, which can be conveniently taken as the average and the maximum waiting time for a vehicle. Traffic simulators are largely used for the purpose. One gets the ability to generate different types of traffic at different times of the day, and study the performance of the handcrafted rules. Looking at the performance, the human designer or, more preferably, an automated system can learn the rules and membership functions.

The problem can also be modelled as an optimization problem (Garcia-Nieto et al., 2011; Kwasnicka and Stanek, 2006; Teo et al., 2010), wherein the aim is to reduce the average waiting time of the vehicles. The waiting time of the vehicles is a function of the traffic signal green time and the operational order. So using simulations for any traffic scenario, the performance for any given traffic-light policy can be computed. This serves as an objective function for the techniques, to be optimized by changing the traffic-light operation time and order. Any optimization technique, like Genetic Algorithm, Particle Swarm Optimization etc. can be used for the optimization.

13.4.2 Intelligent Intersection Management

Waiting at intersections is a common phenomenon which accounts for much of the time of the journey. Intersections and traffic lights lead to properly regulating the flow of traffic. Besides straight roads, intersections form a dominant scenario of operation through which an autonomous vehicle must be able to navigate. Intersections may be controlled or uncontrolled. The *controlled intersections* have traffic lights located at each of the roads and the vehicles can only move when the traffic light is green. This demands the vehicles to have a vision system which can detect and read traffic lights. If the light is green, the conventional trajectory planning mechanisms and algorithms work, although overtaking is rarely conducted. If the light is red, the autonomous vehicle will have to graciously stop with enough distance from the vehicle in front. Intersections with roundabouts mostly have smooth turns for the vehicles to navigate. Sometimes sharp steering may be required at small intersections.

On the contrary, *uncontrolled intersections* do not have any traffic lights to regulate traffic. Going through an intersection is subjected to one’s own decision. Hence, an autonomous vehicle must be able to sense the environment, look at all the vehicles occupying and desirous to occupy the intersection, judge the safety of going through the intersection. Then it must decide whether to go through the intersection or wait for some other vehicle, and, once decided to go through the intersection, make a suitable trajectory and trace that trajectory avoiding all other vehicles passing through the intersection.

To focus upon the perspectives of planning, a simple *intersection management* example is considered. An intersection manager frames policies and plans the flow of vehicles at different roads of the intersection. Here, the work of Dresner and Stone (2004) is discussed. The authors study the *reservation-based intersection management*, wherein a vehicle may reserve its journey at the intersection. The authors first discuss a First-Come-First-Served reservation policy, wherein a vehicle coming near the intersection first attempts to make a reservation. The vehicle specifies the time to reach the intersection, the speed, direction of reaching and the destination direction. The reservation manager, an intelligent agent, simulates if the vehicle can travel without colliding or disturbing any other vehicle passing through the intersection. If the journey is possible, the reservation manager makes the reservation and allows the vehicle to pass through if it reaches at the mentioned time and speed. Otherwise, the reservation is not made and the vehicle may have to wait. If the vehicle fails to reach at the quoted time, it may request cancellation of the previous reservation and make a new reservation. The authors also study uncontrolled intersection management and traffic light-based intersection management.

In another work, Dresner and Stone (2006, 2007) allow for human-driven vehicles which may not have computational devices to make automated reservations at the intersections. Here, the intersection operates using traffic lights. The traffic lights may be operated via different policies, typically allowing all vehicles from one direction simultaneously or allowing vehicles between every source−destination direction pair. The human vehicles may only move when the traffic light is green. However, the automated vehicles are allowed to move even if the traffic light is red, provided they have a valid reservation. Reservations may be requested to the reservation agent in advance. The reservation agent checks whether all kinds of human vehicles with all from−to direction pairs can pass collision free if the reservation is allowed. In such a case the reservation is made and the vehicle is allowed to pass. If some vehicle may potentially have a collision, while operating with the traffic-light policy, the reservation is not made. The resultant bandwidth is hence the normal bandwidth allowed by the traffic light and additional bandwidth allowed by reservations. The reservation policy prohibits reservations which affect the normal functioning of the traffic.

13.4.3 Traffic Merging Management

The overall efficiency of the transportation system stresses the elimination of congestion for which the merging areas play a dominant role. *Merging* denotes the scenarios wherein (normally) two roads merge into one. This is shown in Fig. 13.4. Vehicles from both roads cannot simultaneously enter the merged road unless the bandwidth of the merged road is greater than the sum of the bandwidths of the individual roads, which is rarely the case. Many approaches have been made in the past to effectively

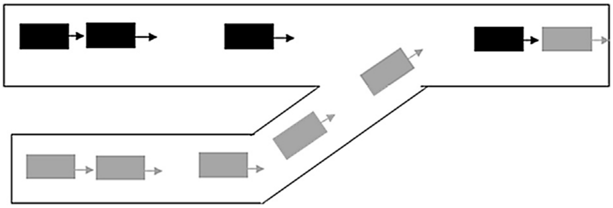

Figure 13.4 Merging scenario.

manage traffic in the merging area. Ramp metering is a popular method to control merging which imposes restrictions on the on-ramp vehicles for entering into the mainline roads (Papageorgiou et al., 1997). The use of the microscopic approach to manage the merging traffic based on the intelligence at the individual vehicle level is also common (Antoniotti et al., 2007). Most of the work related to traffic merging is based on the assumption that the vehicles are automated and equipped with a communication system. Studies have also been carried out in the area of lane distribution for effective implementation of ramp metering. Variable speed limits might change the lane distribution and in turn affect the merging (Carlson et al., 2010).

Merging can be categorized as merging of two highways or freeways, merging of on-ramps into the freeway mainstream, merging within a toll plaza infrastructure and merging of freeway mainstream lanes due to road works (Papageorgiou et al., 2008). For designing any merge-assistance system, there are certain basic questions which are to be addressed like which vehicle of the two traffic streams in the case of two-lane merging, should merge first, what action should be performed by the mainline vehicles and the ramp vehicles to merge at the right time and place etc. The answer depends mainly on the scheduling criterion to be followed between the vehicles of the two streams. Many researchers have been trying to formulate the best type of merging criterion for merging two vehicles efficiently, but the result depends on the effectiveness of the scheduling mechanism employed. The type of merge-assistance system employed depends largely on the types of vehicles involved ie, whether the vehicles are automated and equipped with an effective communication system, semiautomated (limited technological usage) or manual (no automation).

Merging is studied by a small example presented in the work of Raravi et al. (2007), with some adaptations. Consider an intersection of two roads. It is assumed that the number of vehicles at the intersection, the distance of each vehicle from the intersection, the speeds of the vehicles and the maximum speeds and accelerations of the vehicles are known. The vehicles need to move so that a minimum safe distance between all vehicles is always available, whereas the safe distance depends upon the speeds of the vehicles. It is assumed that the vehicles can communicate with the merging manager, which makes the decisions regarding the merging. The algorithm attempts to frame an optimal merging sequence for the vehicles at both streams in the merging scenario.

At any instance of time a decision needs to be made which of the two competing vehicles should go on to the merged road. The scheduling algorithm works on the simple hypothesis that a vehicle which in its normal course of action (without considering the stream of vehicles in the other stream) is projected to reach the intersection first, should be allowed to merge. Them decision regarding which vehicle should be allowed to merge needs to be made as soon as possible to admit a vehicle in the intersection area. The vehicle which takes less time to reach the intersection region is allowed to enter into the merge region.

The time that the vehicle at the head of the lane takes to reach the intersection is calculated from the kinematic parameters of the vehicles. Based on the positions, speeds and accelerations of the vehicles and their current distance from the merged road, the time to reach the intersection can be computed. The vehicle with a lesser time drives through, whereas the other may have to wait for its turn, if the merged road is not clear till it reaches the merging point. In case of any conflict with reference to the time taken to reach the intersection region, the cost to merge associated with the vehicle is taken into account which acts as a secondary factor considered for decision-making. The cost here is the distance of each vehicle from the intersection region at the time of decision-making. The vehicle having the least distance is assigned the least cost and is allowed to enter the intersection region. It is based on the notion that the nearer is the vehicle, the greater the chances it has of adapting itself to any changes. If the distance from the intersection also happens to be the same, then any vehicle may be randomly picked for entrance to the intersection region.

All other vehicles are assumed to be operating on a simple vehicle-following mode, wherein they drive to always maintain a safe distance from the vehicle in front, while trying to drive at high speeds as long as possible. No overtaking may be attempted. Safe distance is computed from knowledge of the relative speeds, vehicle acceleration and current distance. The distance between any two vehicles must be larger than the given safe distance. Speed changes account for acceleration limits.

13.5 Summary

This chapter looked at the complete transportation system, rather than a single vehicle alone, and took the task of understanding the complete system to maximize its performance. The first dominant issue in such a case is the modelling of such a complex system. Traffic-flow theory was explained which relies upon the basic principles of traffic flow, traffic density, mean speed and the relations amongst these. The effect of interrupted traffic in the form of mergers or traffic lights was also studied. Fundamentally, an increase in traffic density reduces the speed of the vehicles, from free-flow speed to a nearly zero congested speed. The flow initially increases to a capacity value and thereafter reduces to a nearly zero value.

These fundamentals were used to make a traffic simulator, which simulates given traffic over a given road network. For this, the traffic simulator should be able to imitate all behaviours of the vehicles including route-choice behaviour, merging behaviour, lane-change behaviour, overtaking behaviour etc. The most important behaviour is the vehicle-following behaviour. The Intelligent Driver Model was discussed for the same.

With this background the task is to make all the components of the transportation system intelligent. The chapter presented the ways of making the traffic lights intelligent to minimize the wait and the queue length on the roads. The intelligent systems try to do so by changing the green-light time and the order of change of traffic lights. The popular methods include fuzzy logic, optimization techniques and reinforcement learning. Similarly, the intersection can be made intelligent by allowing the autonomous vehicles, capable of better control, to pass through the intersection if the same do not conflict with the normal flow of vehicles for the particular state of the traffic lights. The merging can itself be made intelligent by using metrics to decide whether it will be better to allow the ramp vehicle to pass through next or the main-road vehicle.

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